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PROGRESS REPORT 3

THE MEASUREMENT OF MOISTURE GRADIENTS IN CONCRETE PAVEMENT SLABS

AUGUST 1961
NO. 22

by

J. R. BELL

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Progress Report No. 3

THE MEASUREMENT OF MOISTURE GRADIENTS
IN CONCRETE PAVEMENT SLABS

TO: K. B. Woods, Director
Joint Highway Research Project

August 9, 1961

File: 9-7-3
Project: C-36-63C

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

Attached is Progress Report No. 3 on "The Measurement of Moisture Gradients in Concrete Pavement Slabs" by J. R. Bell, Research Engineer, on our staff. This report summarizes the progress made on this study to June 1961 and discusses some of the problems which have been encountered.

The report also proposes that the project be extended to June 30, 1962, without an increase in the budget so that the investigation can include further study of the problems which have been found. Sufficient funds remain in the original budget to continue the project for another year.

This request for extension was officially acted upon by the Board at a previous meeting and the B. P. R. has also taken action by extending the project until December 31, 1961. Further extension will be considered when the 1962 projects are approved.

The report is presented for the record.

Respectfully submitted,

H. L. Michael

H. L. Michael, Associate Director
Joint Highway Research Project

HLM:cw

Attachment

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Joint Highway Research Project
Project No: C-36-63C
File: 9-7-3

Purdue University
Lafayette, Indiana

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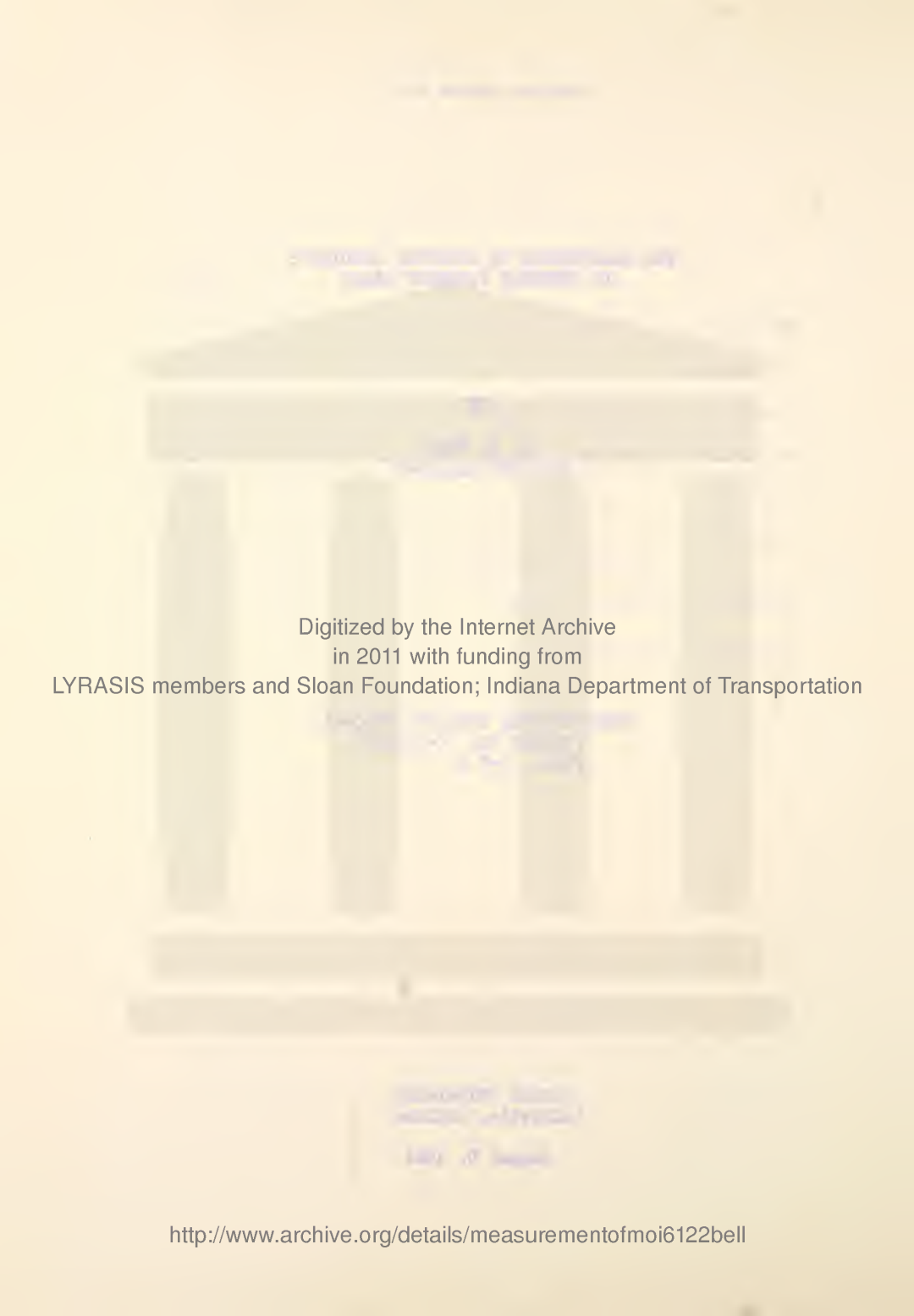
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Progress Report No. 3

THE MEASUREMENTS OF MOISTURE GRADIENTS IN CONCRETE PAVEMENT SLABS

FOREWORD

This study was initiated in February 1958 as a cooperative project with the Indiana State Highway Department and the U. S. Bureau of Public Roads. The purpose of the study was to develop a practical non-destructive test method and the necessary instrumentation to measure moisture gradients in hardened Portland cement concrete pavements under non-steady state conditions.

During 1958 and 1959 a feasibility study of this problem was conducted. The purposes of this study were 1) to conduct a literature search to evaluate the available methods of measuring the moisture content of porous media, 2) to conduct limited laboratory investigations of the more promising of these methods, and 3) to select the most promising method or methods for intensive investigation.

On the basis of the literature survey the dielectric constant (capacitance) method was selected as the most promising. This method was tested by measuring the capacitance of thin mortar disks at various water contents in a parallel plate capacitor by the A. C. bridge method. Two frequencies of bridge operation were used - 60 and 600,000 cycles per second. The results showed these measurements to be very sensitive to changes in water content at low water contents. However, in the higher water content range the method lost much of its sensitivity. This loss was much greater for the 60 c.p.s. tests than for the 600,000 c.p.s. tests. Theory indicated

that this was an instrumentation problem stemming from the fact that the mortar disks exhibit conductance as well as capacitance and was not an inherent problem. Theory also suggested that an additional increase in the bridge frequency would extend the range of sensitivity.

The capacitance measurements are subject to changes in the structure of the concrete with time and reflect the sorption hysteresis in the wetting-drying cycle; however, the test results indicated that the inaccuracies from these causes were not prohibitive and that the data were reproducible. The results of these studies were presented in Progress Report No. 2, "The Feasibility of Measuring the Moisture Gradients in Concrete Pavement Slabs," August, 1959 (1).*

From these studies, it was concluded that the dielectric constant was a satisfactory indicator of water content of hardened concrete and that the capacitance method was worthy of an intensive study to develop the necessary instrumentation to permit in situ moisture measurements by this method. The study was extended to June 20, 1961 to provide for this work.

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* Numbers in parenthesis refer to the bibliography at the end of this report.

INTRODUCTION

Based on the results of the feasibility study an instrumentation study of the capacitance moisture meter was initiated. The purpose of this phase of the project was to develop and test the necessary measuring instruments, sensing elements and procedures to allow in situ field testing of the moisture content of concrete pavement slabs.

The proposal (2) for this study outlined the following method of investigation. The capacitance of an embedded sensing element consisting of two insulated parallel wires was to be measured by the A. C. bridge method. The element would be calibrated by measuring its capacitance in liquids of known dielectric constant, and the dielectric constant-water content relationship for concrete was to be established by capacitance measurements on test disks (similar to those used in the preliminary studies) in a special calibrated parallel plate test capacitor. The final testing of the method and equipment would be by embedding calibrated sensing elements in beams (3" x 4" x 16") of concrete for which the moisture-dielectric constant relationship had been determined. These beams were to be stored under different moisture environments. After suitable periods of time their water contents would be determined by capacitance measurements on the embedded elements. The beams would then be broken and their water content determined by conventional gravimetric methods for comparison.

A one mega-cycle capacitance bridge was purchased from the General Radio Company. This has proven to be an accurate stable high quality piece of equipment. Accessory materials and equipment such as leads, standard dielectric liquids, a temperature control cabinet, etc. were acquired. A test capacitor was designed, built, and calibrated. Using

this capacitor a capacitance moisture content curve was obtained for mortar disk A-C used in the feasibility study. These data showed that the change of capacitance with changes in water content was great enough to provide adequate sensitivity for the method, and the increase in electrical frequency had apparently improved the sensitivity at the higher water contents (see Figure 1). Figure 1 represents averages of the data for disk 8 at 60 c.p.s. (1), disk 0 at 600 kilo-cycles (1), and disk A-C at 1 mega-cycle (Figure 4) all adjusted to have the same relative capacitance scale. Tests showed that sensing elements of the planned design were insensitive, but by substituting narrow, thin, strip conductors lying edge to edge for the wires, a sensing element of excellent sensitivity was developed.

This was the state of the project July 25, 1960, and as the Monthly Progress Report of that date indicated these results were very encouraging, it appeared that the method was nearly ready for the final tests with elements embedded in concrete beams, and that a speedy and satisfactory conclusion to the project was likely. Since that time problems have appeared which have delayed the starting of the final testing program and which make it impossible to anticipate with any certainty what the final outcome will be.

Continued testing has revealed three major problems: 1) the stray capacitances between the sensing element and electrical ground are much larger than expected and are not constant but depend on the proximity of the element to ground. 2) The zone of influence of the sensing element is too large. 3) The measured capacitance is greatly affected by the conductivity of the material being measured. This last item means that the apparent capacitance will be subject to the influences of changes in

the salt concentration of the pore water in the concrete. Increasing the bridge frequency to one mega-cycle has not eliminated this problem.

The problem of the influence of conductivity on the measured capacitance was considered to be of a more fundamental nature than the other two which are primarily problems of instrumentation; therefore, most of the work during the past several months has been devoted to a study of this problem. It was reasoned that if this was an inherent limitation which would make the method impractical there was little need to solve the problems of instrumentation; therefore, study of the first two problems has been deferred until the latter one is better understood.

PROCEDURES AND SUMMARY OF RESULTS

As pointed out in Progress Report No. 2 the apparent capacitance of a real capacitor as indicated by an A. C. capacitance bridge measurement is not the true capacitance of the capacitor. The true capacitance depends only on the geometry of the capacitor and the dielectric constant of the dielectric material within the capacitor and for a given frequency is a constant. The apparent capacitance indicated by an A. C. bridge is not only a function of the electrical frequency of the bridge but also of the circuit containing the capacitor in question and the conductivity of the dielectric material within the capacitor. To measure the capacitance by the A. C. bridge method, the unknown capacitor is inserted into one arm of an instrument similar in principle to the familiar Wheatstone bridge. By adjustment of appropriate components in the bridge, the flow of current through the null indicator can be made equal to zero. At this adjustment the dial readings on the adjustable bridge components indicate a capacitance and a resistance which at the frequency of the measurement are electrically equivalent to the unknown capacitor and its associated circuit. This is illustrated in Figure 2. The circuit in the right hand block of Figure 2 is the assumed schematic circuit of the test circuit seen by the bridge. It includes the unknown capacitance (C_x), the capacitance of the insulation on the capacitor plates and the contact capacitor (C_i), the fringe capacitance and stray capacitance to ground (C_g), and the capacitance of the leads between the capacitor and the bridge (C_l). These capacitances are not ideal but have power losses; therefore, they are shown as an equivalent circuit composed of an ideal capacitor and a parallel resistance. These resistances have meaning only in the sense that when placed across an ideal

capacitor of the same capacitance as the real capacitor they provide the same power loss for the system as the real capacitor. The components in the left hand block are the capacitance and resistance indicated by the bridge readings such that their impedence (Z_b) is equal to the impedance of the unknown circuit (Z_t) in both magnitude and phase.

Assuming this model, the problem is to determine the capacitance (C_x) of the concrete (mortar in these studies) from the bridge readings C_b and R_b. For a given test set up it was assumed that the characteristics of the leads, the insulation, and the stray capacitances are constant. With this assumption it is possible through the well known laws of A. C. circuits to express the unknown quantities R_x and C_x in terms of the circuit constants and the bridge readings and to calculate the dielectric constant of the material in the test capacitor (see Appendix A for an outline of these calculations).

Before these equations could be applied it was necessary to evaluate the equipment and circuit constants. The capacitance and equivalent parallel resistance of the leads were determined by simply connecting the leads to the bridge and measuring them. The fringe capacitance and stray capacitance to ground was evaluated by measuring the capacitance of the test capacitor with air as the dielectric for several different spacings of the plates. The difference between the measured values and the geometric capacitance was taken as equal to these stray effects. The capacitance of the insulation on the capacitor plates was determined from direct measurements with the insulated capacitor plates clamped together.

To check the above theory and equipment constants, a series of tests using liquids was conducted. The capacitances of five liquids of known dielectric constant were measured in the test capacitor. The liquids and

their dielectric constants are listed in Table I. The apparent capacitance was determined by simply subtracting the capacitance of two leads from the measured values. The "true" capacitance was calculated from the measured data using the previously described theory. From these capacitances the apparent and true dielectric constants were calculated. These results are shown in Figure 3. From these data it can be seen that there is considerable error in the apparent dielectric constant, but the calculated "true" dielectric constant is very nearly equal to the known dielectric constant for all liquids measured.

With this evidence to support the test and analytical procedures, tests were conducted to determine if the "true" dielectric constant of mortar could be determined in the same manner, to check repeatability between samples, to evaluate the dielectric constant-water content relationship for a mortar, and to investigate the influence of the salt concentration of the pore water in the mortar. The following test series were performed:

1) Capacitance vs. water content for disk A-C initially saturated with distilled water.
2) Capacitance vs. water content for disk B-C initially saturated with distilled water
3) Capacitance vs. water content for disk A-C initially saturated with 1.0 N. NaCl solution.
4) Capacitance vs. NaCl concentration for water.

The tests on mortar disks were performed in essentially the same manner as the tests in the previous low frequency tests and are described in Progress Report No. 2 (1). The disks A-C and B-C were disks used in these earlier tests. Preliminary tests indicated that they were sufficiently aged to be structurally stable and showed no shifting of the data on

subsequent runs. For the tests using liquids, a thin-wall plastic cylinder 0.15 inches high was cemented to the bottom plate of the capacitor to contain the liquid during the test. All tests were run at a temperature of 30°C and a bridge frequency of one mega-cycle.

The test data are presented in Figures 1 through 8 and the dielectric constants calculated from these data are presented in Figures 9 and 10.

DISCUSSION OF RESULTS

There are several aspects of these data which are apparent from the capacitance water content curves: 1) The data are reproducible. The curves for disk A-C for July, 1960 and for March, 1961 show very good agreement. The test set-up had been completely disassembled between the times these two sets of data were taken. 2) The results are relatively consistent between samples. Only two different disks were tested, disks A-C and B-C, and they were both from the same mortar batch. But this correlation is at least encouraging. 3) The range of water contents over which the method has acceptable sensitivity covers nearly the full range from oven dry to saturation. These results are all positive. On the negative side the hysteresis in the wetting-drying cycle is still apparent. If anything, it is greater than it was at the lower frequencies. The most serious effect shown by these data is the very large discrepancy between the results for distilled water and for salt water saturation. The strong influence of the ion concentration of the water is also shown by the data from the tests on salt water of various concentrations (Figure 7).

According to the model assumed for the mortar as a dielectric and the theory derived for this model, it should be possible to take this data and calculate the true dielectric constant-water content relationship for each of the test series. If the theory is correct, all of the data represented by Figure 8 should be reduced to a common relationship. The results of such calculations are presented on Figures 9 and 10, which show the successes and failures of this method of analysis.

The calculated dielectric constant-water content relationships for all cases using distilled water shows excellent agreement, the sensitivity

has not been reduced, and the hysteresis effect has been somewhat reduced. However, this theory completely fails to remove the effects of adding NaCl to the pore fluid.

While these results are discouraging, they do not in themselves rule out the possibility of developing a satisfactory capacitance type moisture meter. Two possibilities for a successful solution still exist. The first is an empirical method based on the apparent capacitance and making no effort to calculate the true dielectric constant. It is possible that during the normal life of a concrete pavement the ion concentration of the pore fluid in the concrete would never vary enough to appreciably influence the apparent capacitance. The apparently low concentration of the pore fluid in the mortar disks used may be the result of leaching during numerous cycles of wetting and oven drying. The data for the 600 kilocycle tests indicated that increasing the salt concentration of the pore fluid of a relatively fresh disk had negligible effect.

The empirical method would have several disadvantages. First, one would never really know whether or not changes in pore fluid composition were influencing the results. At best it could only be determined that such effects were relatively improbable. Second, the calibration procedures would also have to be empirical and established for each mix. They could not utilize standard dielectric liquids as discussed in the Proposal submitted August 5, 1959 (2). This would make calibration more time consuming and less accurate. The temperature corrections would also have to be determined empirically, and therefore, they would also be less accurate and more time consuming.

The second and preferable method if feasible is an analytical method. The failure of the theory discussed in a previous section does not eliminate

this approach. The model assumed to represent the soil-to-soil electrical properties of the mortar was the simplest of several possible (9). In this model it was assumed that all of the power loss in the mortar was due to ohmic conductivity. Power losses in the mortar dielectric due to polarization and other factors are probably considerable and evidently dependent upon the ion concentration of the pore fluid. Any method based on a more elaborate model for the dielectric would have the disadvantage of requiring laborious (unless programmed for a computer) calculations and would require ancillary measurements, but if possible would have the considerable advantages of being free of the effects of pore fluid composition and of requiring relatively simple calibration procedures. A rational analytic method is considered desirable if possible.

CONCLUSIONS AND RECOMMENDATIONS

The investigations to date lead to the following conclusions:

1) The range and sensitivity of the method is good.

2) For low ion concentrations of the pore fluid a dielectric constant-water content relationship can be determined which is reproducible.

3) The simple model of a capacitor and a resistor in parallel does not appear to describe adequately the dielectric properties of the mortar with high salt concentration of the pore fluid.

4) The investigations to date are inconclusive: it is not yet known whether or not a reliable capacitance type moisture meter can be developed.

In the light of these conclusions it is recommended that the project be extended to continue these investigations. Specifically it is recommended that the research program be extended for another year to permit further theoretical studies aimed at an adequate analytical approach, and a study of the susceptibility of fresh mortar to changes in salt concentration (and other factors) to evaluate the purely empirical approach. The project budget contains a sufficient amount to continue this work for another year (until June 30, 1962). The provisions for personnel, reports, and supervision of the project would remain the same during this one year extension as they have been in the past.

APPENDIX A

Outline of Calculations for Dielectric Constant

The following is an outline of the method for calculating the dielectric constant (e_x) of the material in the test capacitor from the capacitance bridge readings and circuit constants (i.e.: from the following data)

Data:

Variables:

C_{bs} - Bridge capacitance reading

D - Bridge dissipation factor reading

Constants:

$w = 2\pi f$ - f is bridge frequency (c.p.s.)

C_o - Geometric capacitance of test capacitor

C_l - Capacitance of leads

R_l - Effective parallel resistance of leads

C_s - Stray capacitances

R_s - Effective parallel resistance of stray capacitances

C_i - Capacitance of insulation on capacitor plates

R_i - Effective parallel resistance of capacitor plate insulation

Required:

e_x - Dielectric constant of material between plates of test capacitor.

See Figure 2 for the schematic diagram of the assumed test circuit and equivalent circuit.

The expression for the direct calculation of ϵ_r from the data is extremely difficult to use for hand calculations. For convenience the calculation can be accomplished in several steps.

1) Calculate C_b and R_b (see Figure 2)

$$C_b = \frac{C_{bs}}{1 + D^2} \qquad (1)$$

$$R_b = \frac{1 + D^2}{D w C_{bs}} \qquad (2)$$

2) Calculate new lumped circuit components (C_b' & R_b') to form a parallel circuit equivalent to the test circuit with the effects of the leads removed.

$$C_b' = C_b - C_l \qquad (3)$$

$$R_b' = \frac{R_b R_l}{R_l - R_b} \qquad (4)$$

3) Remove the effects of the stray capacitances from C_b' and R_b' and calculate a new equivalent parallel circuit composed of C_b'' and R_b''

$$C_b'' = C_b' - C_s \qquad (5)$$

$$R_b'' = \frac{R_b' R_s}{R_s - R_b'} \qquad (6)$$

4) Calculate C_x

$$C_x = \frac{(Y - B)}{(X-A)^2 + (Y-B)^2 w^2} \qquad (7)$$

where:

$$A = \frac{R_i}{1 + (w R_i C_i)^2} \qquad (7a)$$

$$B = A R_i C_i \qquad (7b)$$

$$X = \frac{R_b}{1 + (w R_b'' C_b'')^2} \qquad (7c)$$

$$Y = X R_b'' C_b'' \qquad (7d)$$

5) Calculate e_x

$$e_x = \frac{C_x}{C_o} \qquad (8)$$

6) R_x may be determined from:

$$R_x = \frac{(X - A)^2 + (Y - B)^2 w^2}{(X - A)} \qquad (9)$$

APPENDIX I

Tables and Figures

Table I. Standard Liquids

No.	Liquid	Dielectric Constant at 20°C*
1	Carbon Tetrachloride	2.2
2	Chlorobenzene	5.5
3	1,2 -Dichloroethane	10.1
4	Methanol	31.6
5	Water	76.7

* Data from National Bureau of Standards (4).

Fig 1 - [illegible]

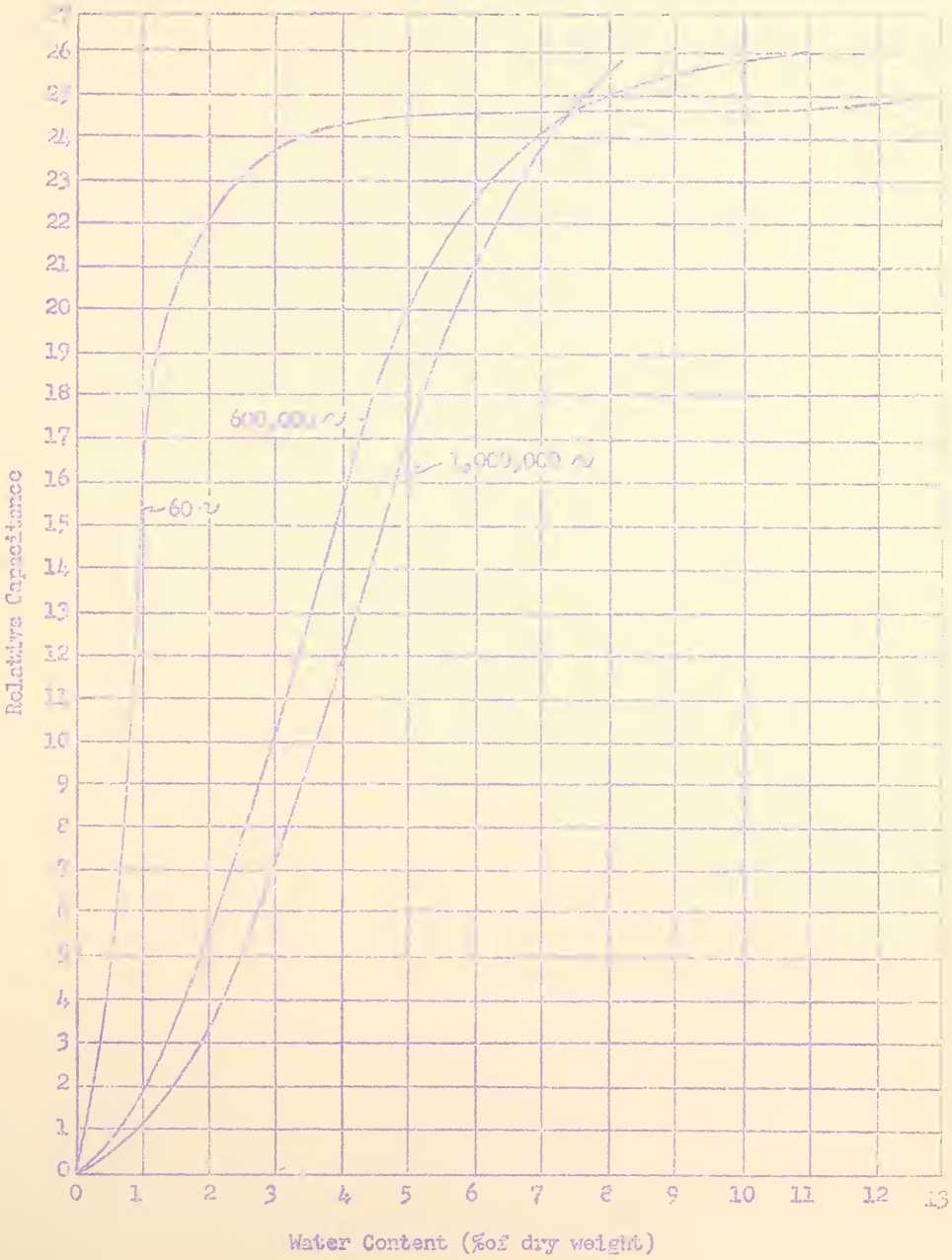
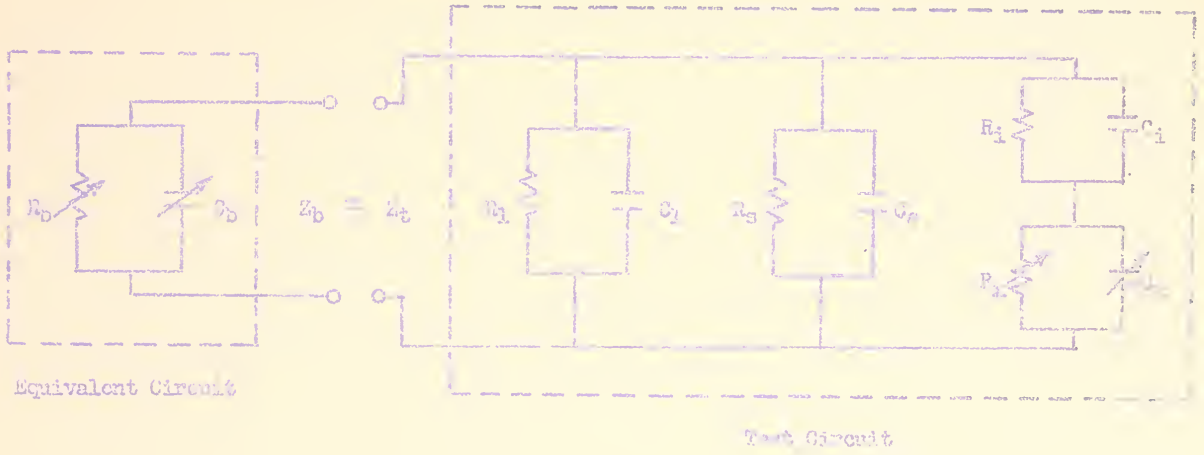
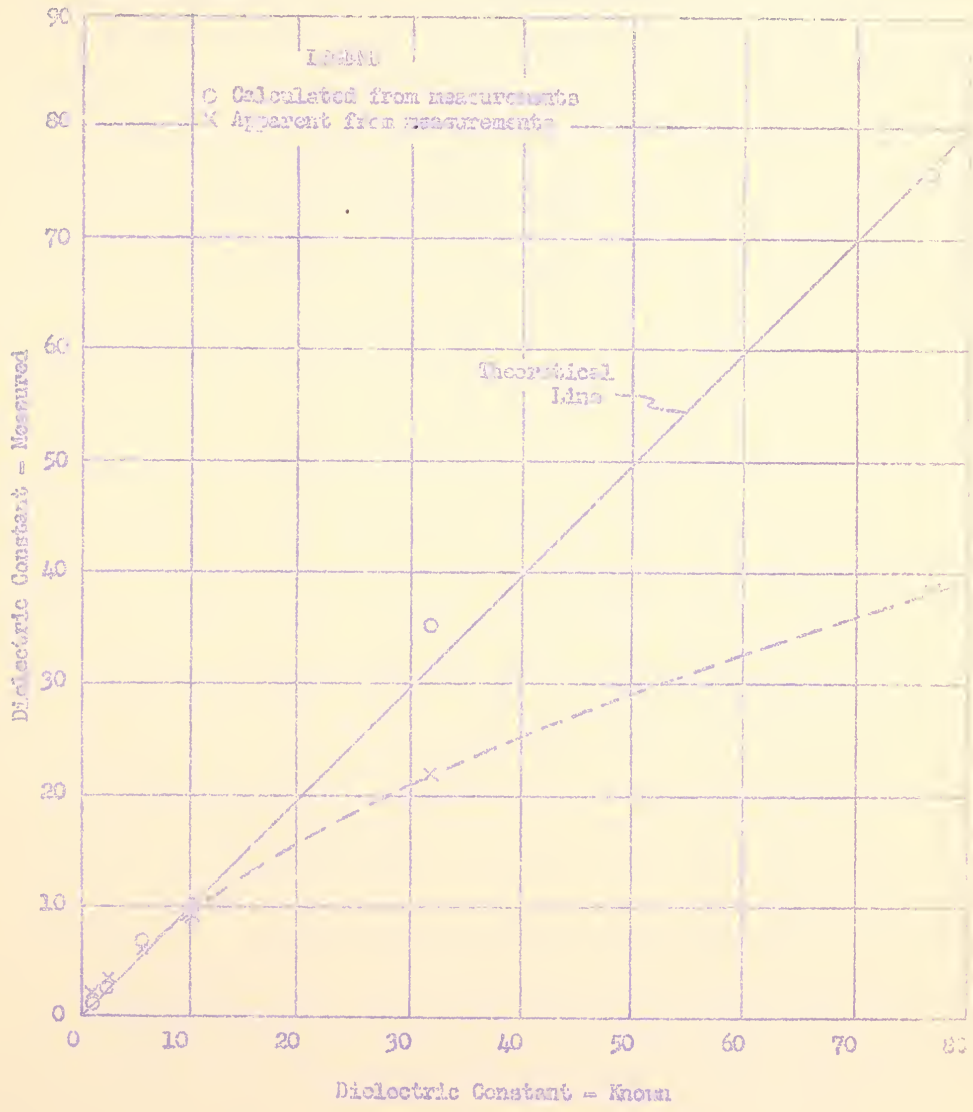
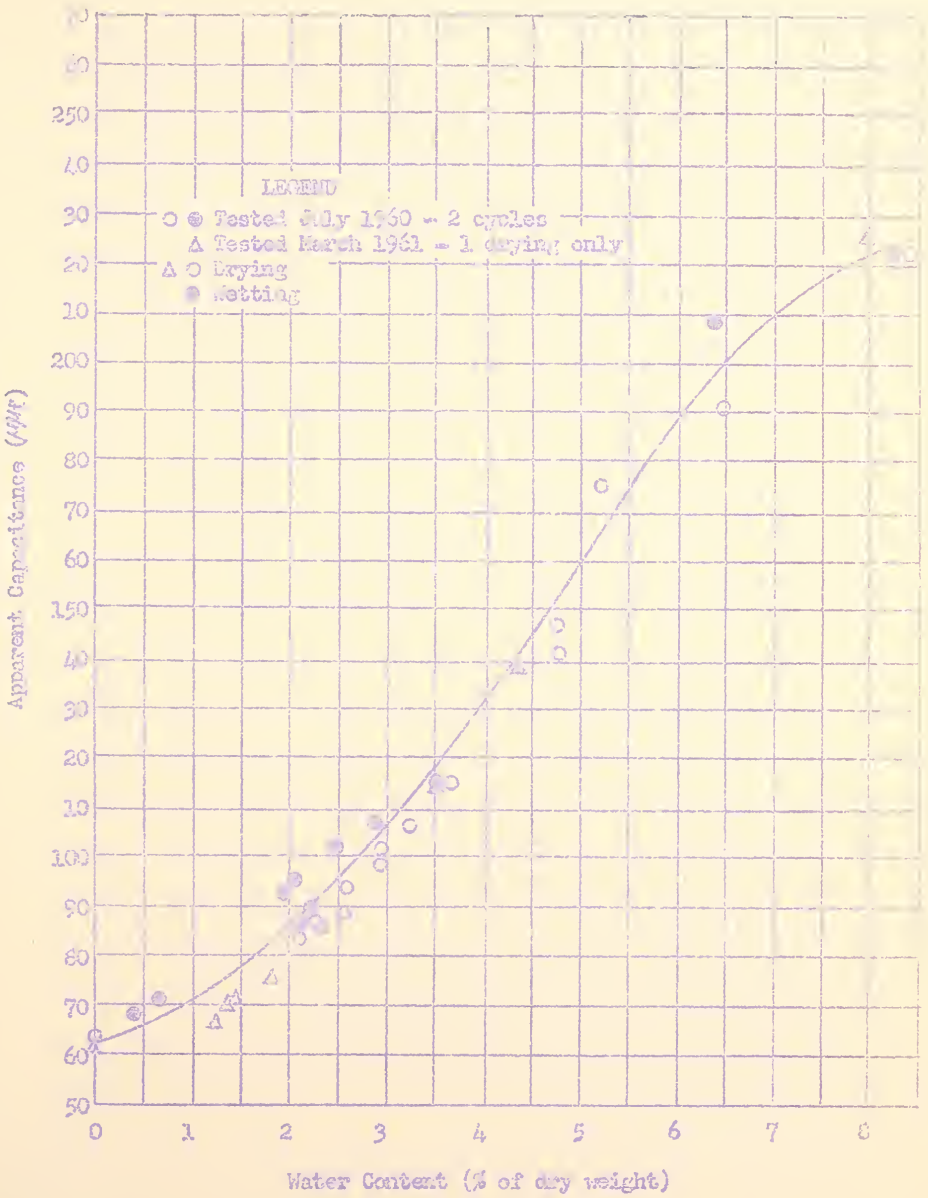
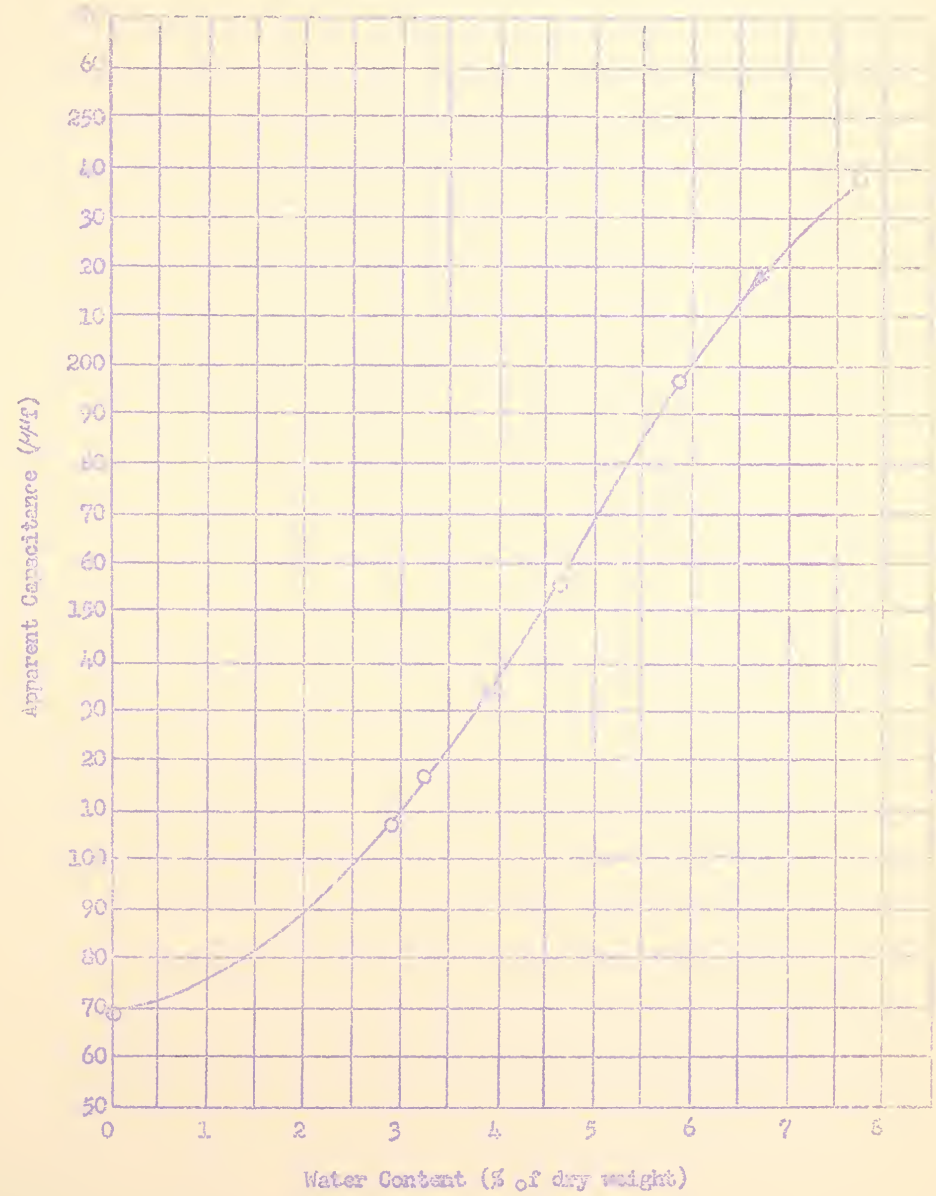

Relative Capacitance
Water Content (% of dry weight)
600,000 ~
1,000,000 ~
~60 ~

FIG. 2 — SCHEMATIC DIAGRAM OF TEST CIRCUIT AND OF EQUIVALENT CIRCUIT




O Calculated from measurements
X Apparent from measurements
Theoretical Line
Dielectric Constant = Measured
Dielectric Constant = Known
0
10
20
30
40
50
60
70
80
90


LEGEND
○ ● Tested July 1960 - 2 cycles
Δ Tested March 1961 - 1 drying only
Δ ○ Drying
● Wetting
Apparent Capacitance (μμf)
Water Content (% of dry weight)
0
1
2
3
4
5
6
7
8
50
60
70
80
90
100
150
200
250


Apparent Capacitance (μμf)
Water Content (% of dry weight)
0
1
2
3
4
5
6
7
8
50
60
70
80
90
100
200
250

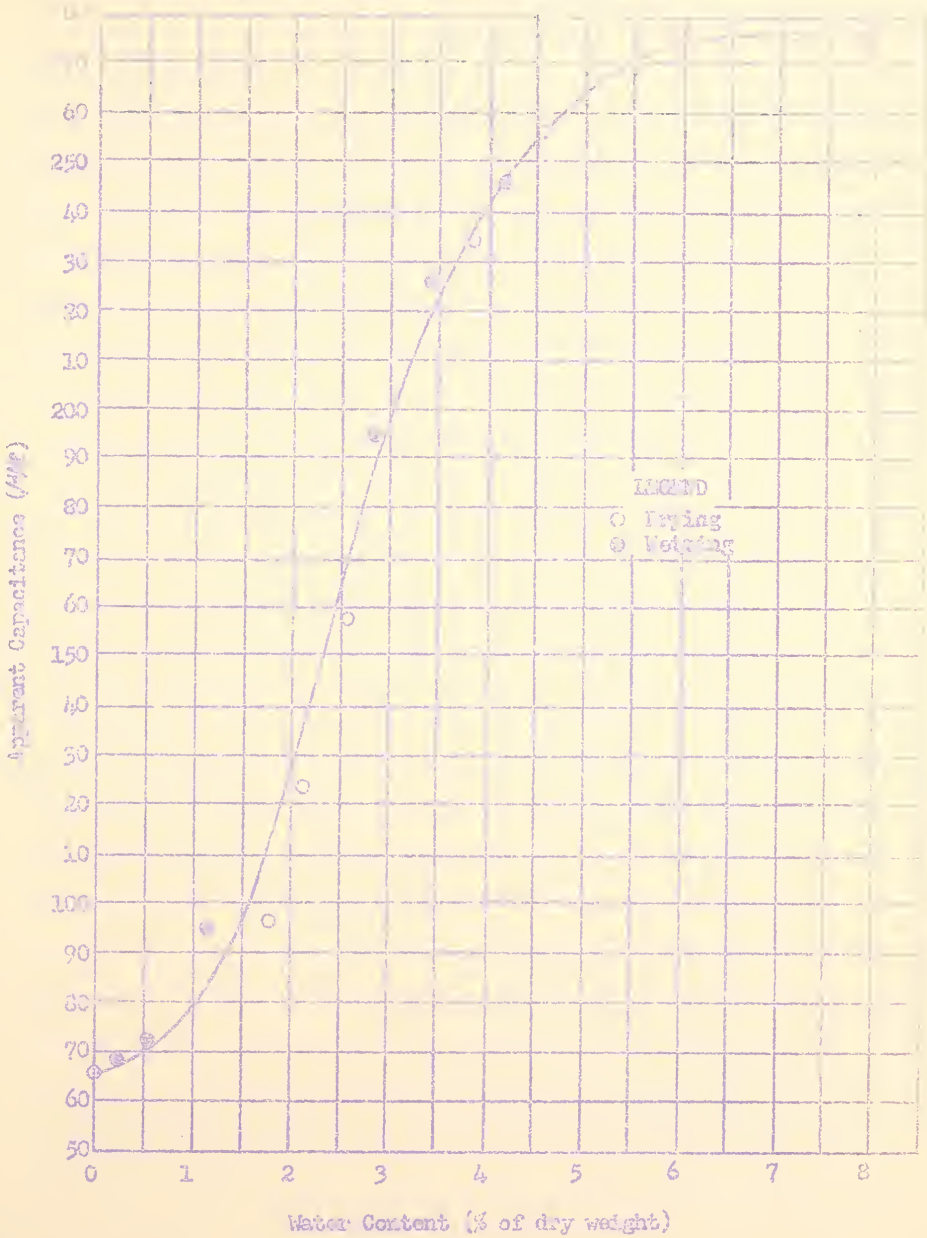
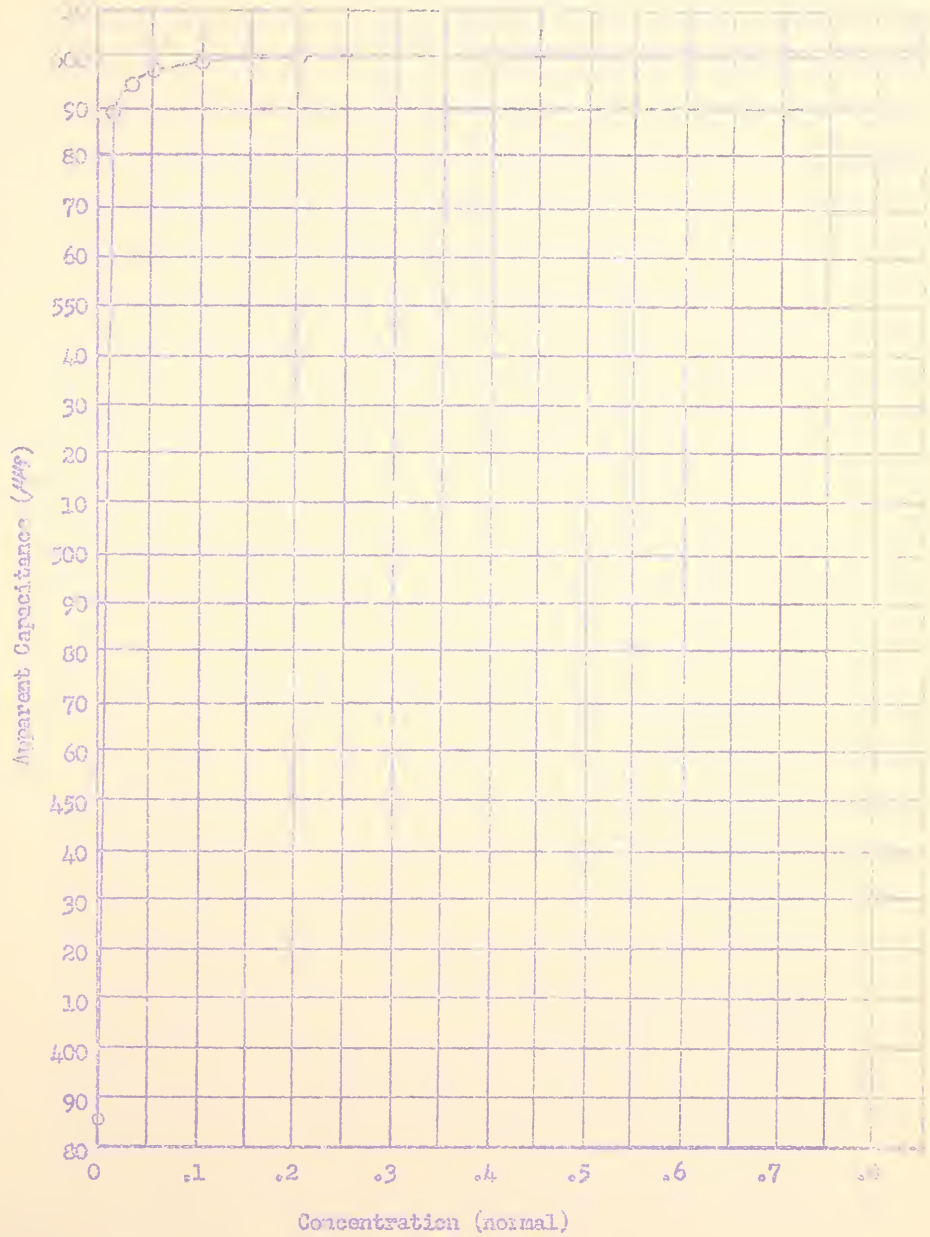
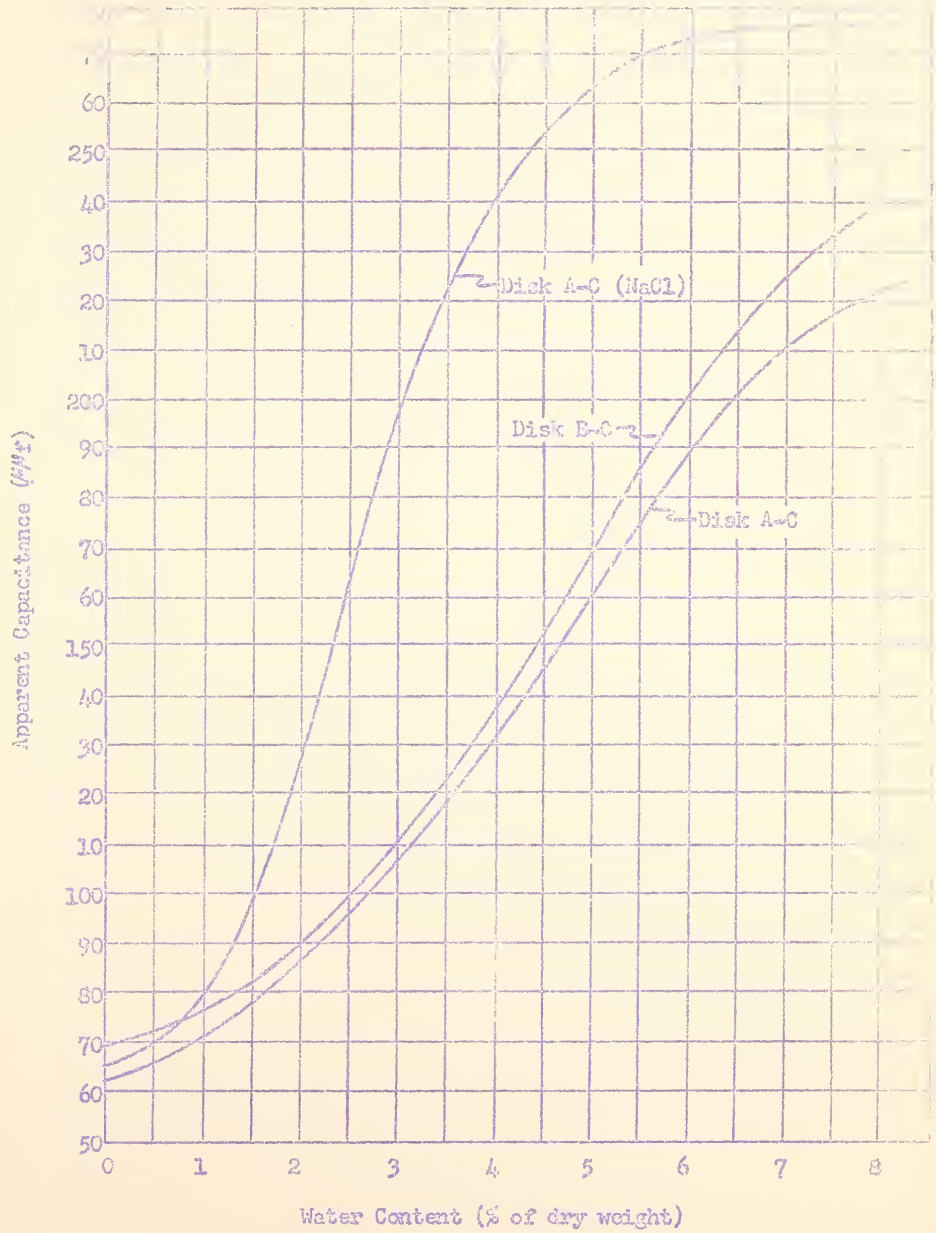
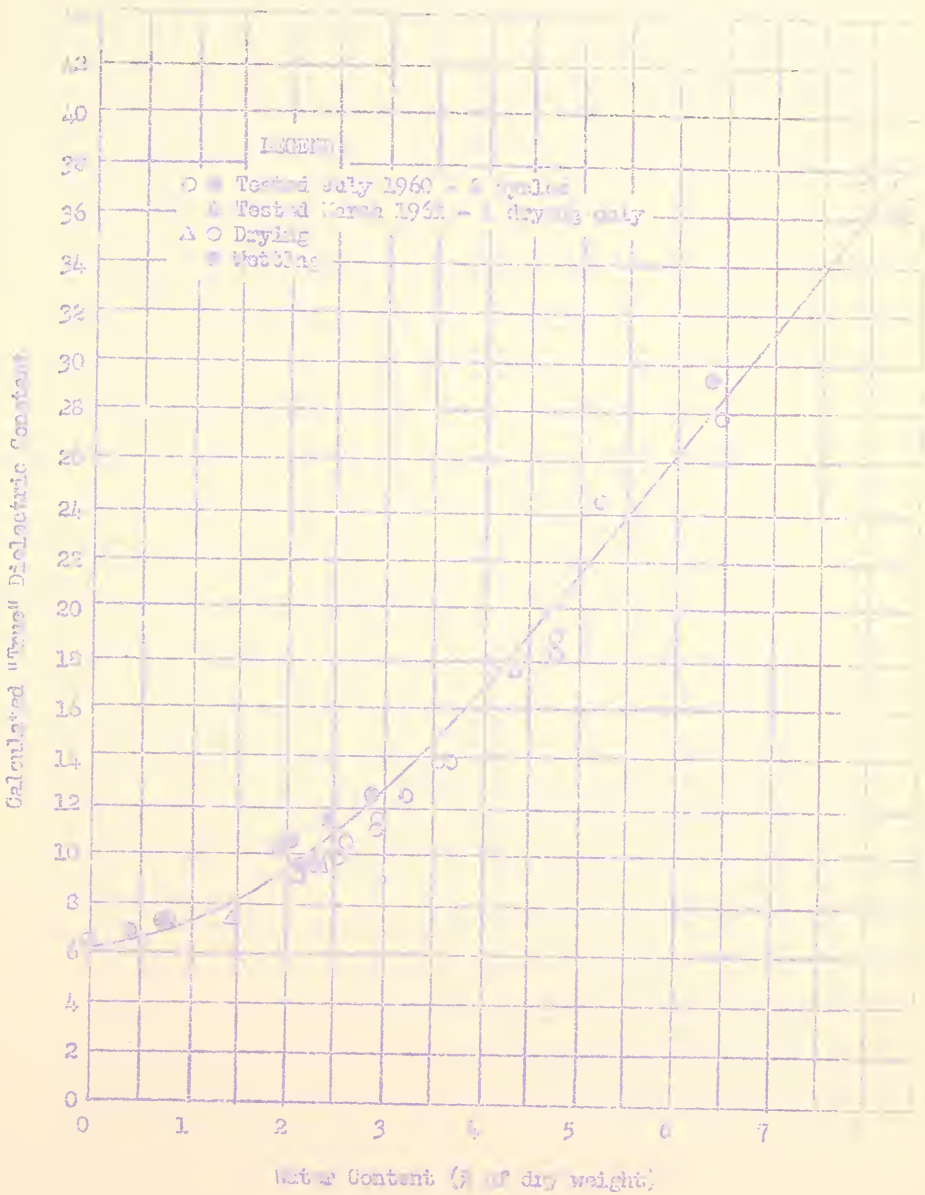
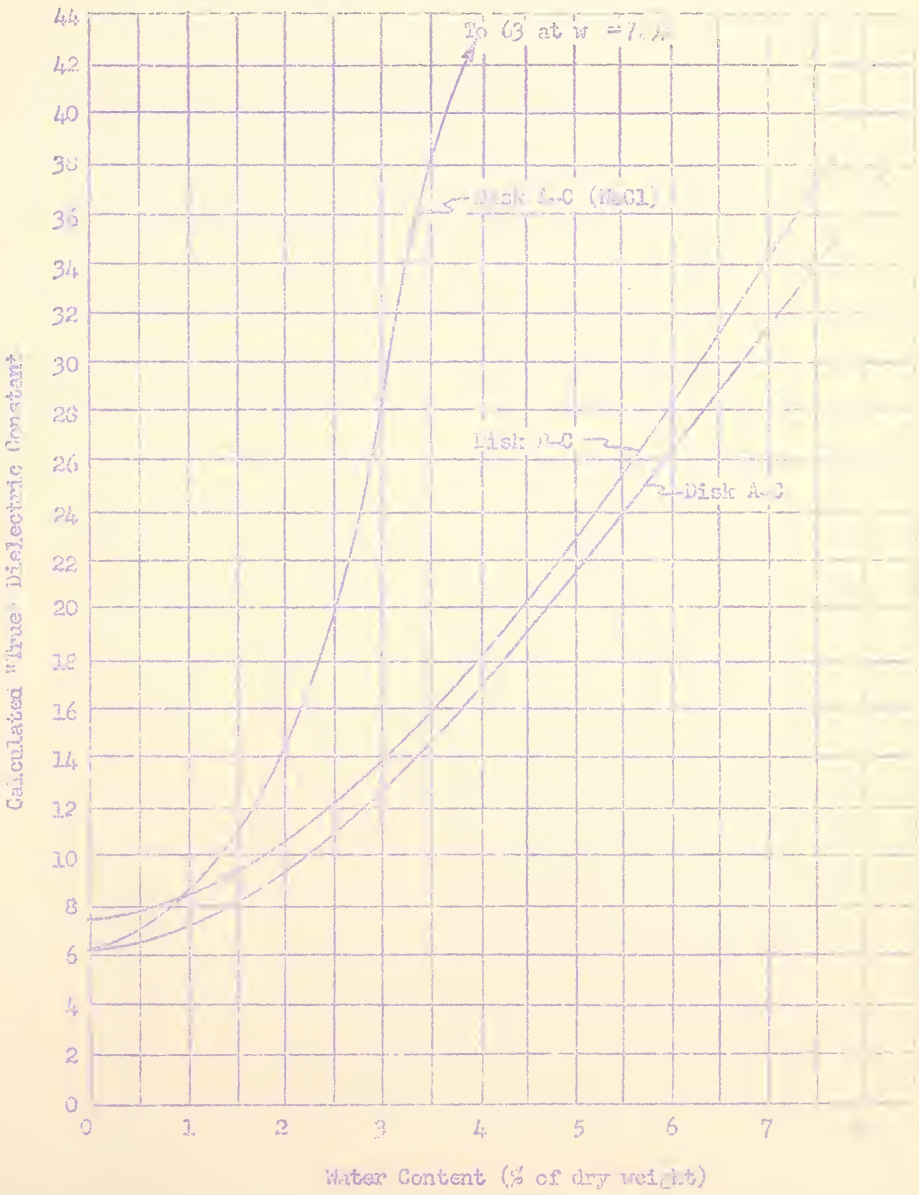

Apparent Capacitance (μμf)
Water Content (% of dry weight)
0
1
2
3
4
5
6
7
8
LEGEND
Drying
Wetting

FIG. 7 - [illegible]




Disk A-C (NaCl)
Disk B-C
Disk A-C
Apparent Capacitance (μμf)
Water Content (% of dry weight)
0
1
2
3
4
5
6
7
8
50
60
70
80
90
100
10
20
30
40
150
60
70
80
90
200
10
20
30
40
250
60


LEGEND
Tested July 1960 - 6 cycles
Tested March 1961 - 1 drying only
Drying
Wetting
Calculated "Bound" Dielectric Constant
Water Content (% of dry weight)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
0
1
2
3
4
5
6
7


To 63 at w = 7.1%
Disk A-C (NaCl)
Disk B-C
Disk A-C
Calculated "True" Dielectric Constant
Water Content (% of dry weight)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
0
1
2
3
4
5
6
7

1. Bell, J. R., "The Feasibility of Measuring Moisture Gradients in Concrete Pavement Slabs," Progress Report No. 2, Joint Highway Research Project, Purdue University, August, 1959.

2. Bell, J. R., "The Measurement of Moisture Gradients in Concrete Pavement Slabs," Proposal for Extension of Research, Joint Highway Research Project, Purdue University, August, 1959.

3. Von Hippel, A. R., "Dielectrics and Waves," John Wiley and Sons, Inc., (1954).

4. Marott, A. A. and Smith, E. R., "Table of Dielectric Constants of Pure Liquids," Circular 514, National Bureau of Standards, U. S. Department of Commerce, August, 1951.